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ORIGINAL ARTICLE

Beyond Intensity: How Rainfall Accumulation Patterns Drive Flood Disaster Characteristics in Southern Brazil

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Abstract

This paper investigates the role of extreme rainfall in major flood disasters in Southern Brazil. Disaster Information System Brazil (S2ID) from 1991 to 2024 was consulted to identify the key variables best representing the magnitude of damage, through a hierarchical ranking of the First Principal Component. We hypothesize that accumulated extreme rainfall, rather than isolated intense events, constitutes the primary driver of large-scale flood disasters in the region. We investigated precipitation characteristics and extreme events occurring in the 15 largest flood disaster events. We used historical daily precipitation series data from 13 weather stations. with quality control performed by CoRain software for rain series comparison. Accumulated extreme rainfall contributed to 67% of major flood disasters in southern Brazil. The remaining 33% is linked to isolated extreme rainfall events. These isolated extreme events intensified hydrological disasters through rapid runoff generation and soil saturation feedbacks. While the total rainfall volume showed a decreasing trend in 2 municipalities and an increasing trend in 5, all studied municipalities exhibited an increasing trend in the frequency of extreme rainfall events. These results are consistent with intensification patterns observed in other subtropical regions globally. Our findings indicate that the sequential occurrence of rainfall events, culminating in significant accumulated volumes, emerges as the principal conditioning factor for large-scale hydrological disasters in the region. This scenario is associated with quasi-stationary frontal systems and persistent cyclonic activity, particularly the prolonged influence of the South Atlantic Polar air masses. These findings contribute to understand mid-latitude flood generation mechanisms, with implications for early warning systems and adaptation strategies in subtropical regions worldwide.

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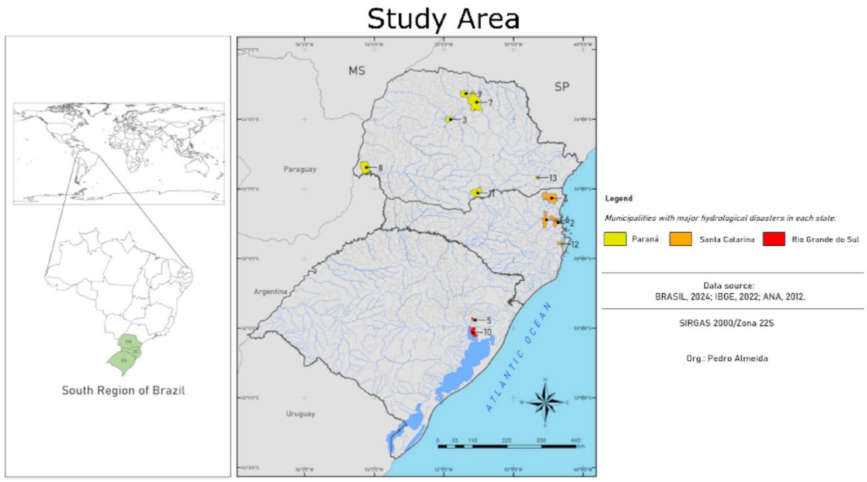
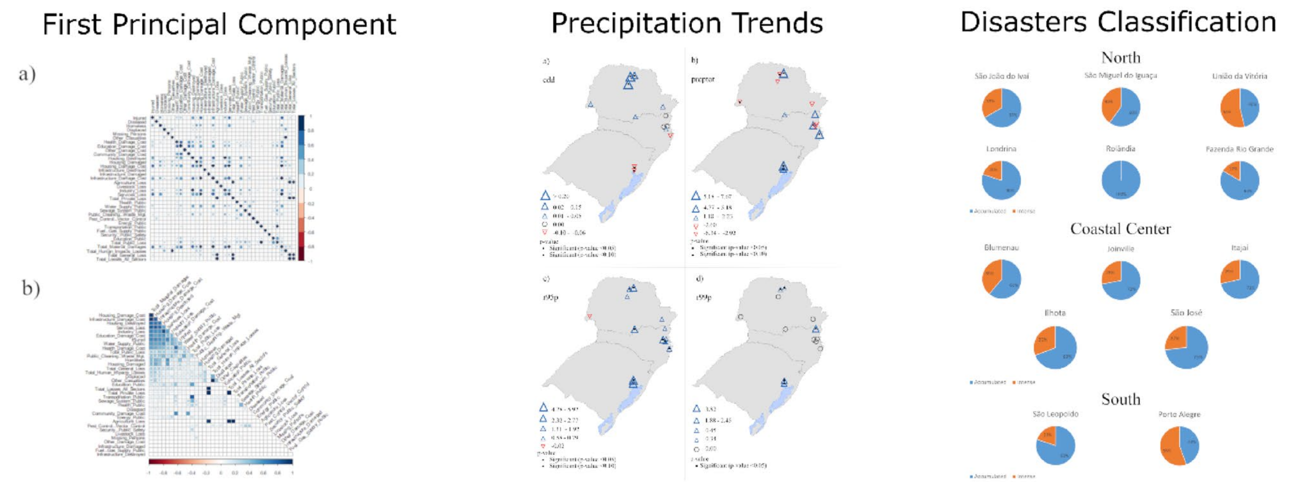
Graphical Abstract



Major hydrological disasters in southern Brazil (1991 – 2024)

Order	Municipality	State	Total material damage
1	Blumenau	SC	R$ 1.618.922.680,00
2	Itajaí	SC	R$ 1.057.143.355,00
3	São João do Ivaí	PR	R$ 355.369.909,90
4	Joinville	SC	R$ 334.900.704,60
5	São Leopoldo	RS	R$ 154.921.000,00
6	Ilhota	SC	R$ 153.868.748,20
7	Londrina	PR	R$ 151.502.080,60
8	São Miguel do Iguaçu	PR	R$ 144.294.077,40
9	Rolândia	PR	R$ 135.283.794,90
10	Porto Alegre	RS	R$ 134.605.356,30
11	União da Vitória	PR	R$ 131.798.327,70
12	São José	SC	R$ 109.814.074,60
13	Fazenda Rio Grande	PR	R$ 101.438.731,70



This graphical abstract synthesizes the spatial, statistical, and climatological dimensions of extreme precipitation across Southern Brazilian municipalities that recorded major flood disasters (with damages exceeding 100 million BRL). Data sources include the Brazilian Disaster Information System (S2ID) for the 1991–2024 period, combined with historical daily precipitation series from 13 weather stations, processed after systematic quality control using the CoRain software. The Analyses utilize correlation matrices and Principal Component Analysis (PCA), establishing total material damage as the most representative variable of disaster magnitude. The Model evaluates trends in precipitation indices (such as r95p and r99p) and examines rainfall characteristics over the preceding 30 days for 137 major events. These cases were categorized by their conditioning typology: intense isolated or accumulated rainfall. Results, visualized through trend maps and pie charts, reveal that 67% of major flood disasters were triggered by accumulated rainfall, whereas 33% resulted from isolated extreme events. The Conclusion highlights that sequential rainfall, driven by quasi-stationary frontal or cyclonic systems, is the primary factor for large-scale disasters. This synthesis advances the understanding of complex climate-disaster interactions, offering essential insights for early warning systems by distinguishing between isolated and accumulated rainfall drivers, thereby fostering risk mitigation and community resilience.

Highlights

- Rain-generated flood disasters (1991–2024) in Southern Brazil reveal 30-day accumulated rainfall as a more critical trigger than isolated intense events.
- Accumulated extreme rainfall causes 67% of major flood disasters, while isolated events account for the remaining 33%.
- PCA establishes a hierarchical ranking of damage variables, providing a novel framework to quantify hydrological disaster magnitude.
- Results demonstrate an increasing trend in R95p and R99p extreme rainfall events across Southern Brazil.

- Consistent rainfall series via CoRain gap-filling enhance early warning systems by distinguishing between isolated and accumulated rainfall triggers.

Keywords Extreme Precipitation · Hydrometeorological Hazards · Rainfall · Disaster Analysis · Hydroclimatology · Climate Change

1 Introduction

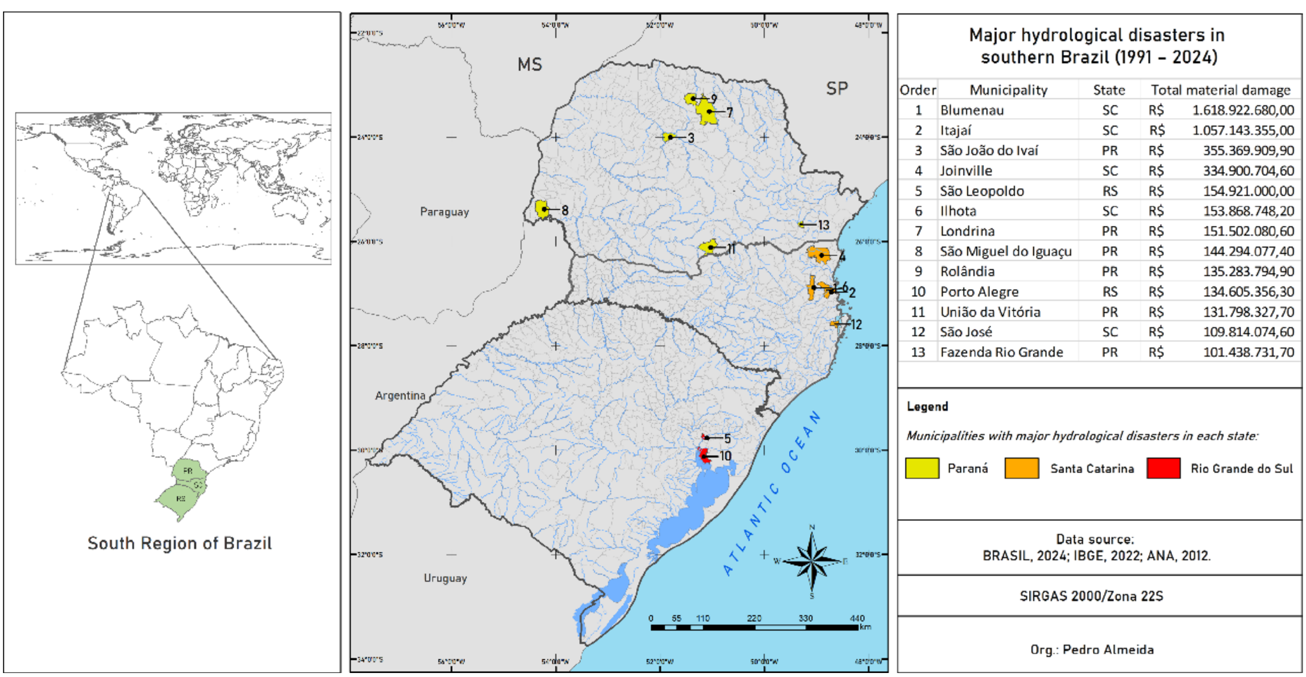
Extreme precipitation events represent one of the most significant natural hazards affecting human populations globally, with flood disasters causing substantial loss of life and economic damage (IPCC, 2021; Blöschl et al. 2019). Floods are a leading cause of natural disasters, often resulting in substantial loss of life and property damage, particularly in urban environments (Manandhar et al. 2023). Human activities, climate, topography, and hydrology are factors that influence the incidence of floods (Machado and Vestena 2024).

Globally, 1,027 flood-related natural disasters were recorded between 2017 and 2023, with 166 events occurring in 2023 alone (EM-DAT, 2024a). The number of people affected by these events has rapidly grown over the years and forecasts indicate that the damage caused will increase significantly in the coming years (Brazil 2013; EM-DAT, 2024b).

Climate change is one of the most significant challenges of the 21st century, with widespread impacts on all populations. It strongly affects weather patterns, increasing the frequency and magnitude of extreme events, such as floods and intense rainfall (IPCC, 2021).

In Brazil, particularly in the southern region, hydrological disasters have intensified in recent decades, affecting millions of people and generating billions of dollars in economic losses (Marengo et al. 2021; Debortoli et al. 2017). The country hosts 13,948 floodable river segments across 2,780 distinct watercourses, with 30% exhibiting high vulnerability to gradual flooding (Brazil, 2014). Furthermore, in 2022, 34.9% of municipalities (1,942 out of 5,570) were identified as most susceptible to landslides, mudslides, and floods, involving 8,904,136 individuals (6.1% of the Brazilian population) living in geohydrological risk zones (Brazil, 2023).

Between 1991 and 2024, hydrological disasters in Brazil caused substantial human and material damage. Recorded human impacts included 4,549 fatalities, 9.81 million displaced and homeless, 681.67 million injured and sick, and 10.5 million affected individuals. Economically, total losses reached R$ 138.91 billion, with R$ 29.32 billion in public damages and R$ 140.19 billion in private damages (Brazil et al. 2024a).



Order	Municipality	State	Total material damage	
1	Blumenau	SC	R$	1.618.922.680,00
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Fig. 1 South Brazil region and spatial distribution of affected communities; the table on the left shows the municipalities that incurred in the most significant damages (expressed in R$)

In Brazilian records, hydrological events result in the highest rates of exposure (67.5%), morbidity (63.5%), and mortality (44.8%) (Freitas et al. 2014). Flood disasters accounted for 32.7% of all events in Brazil, 40.3% of those affected, 44.8% of mortality, 63.5% of morbidity, and 67.5% of those exposed, primarily displaced and homeless individuals (Freitas et al., 2014). The highest number of flash floods recorded occurred in the Southern region and showed an increasing frequency (Brazil et al. 2024a).

In southern Brazil, the disasters that cause the most deaths are those of hydrometeorological origin, for example, the event that occurred in May 2024 in Rio Grande do Sul which affected another 2.3 million people and caused more than 160 deaths (CNM, 2024; Clarke et al. 2024). Such events underscore the urgent necessity to investigate the multi-scale atmospheric drivers that transcend simple intensity metrics (Reboita et al. 2024).

A large number of flash floods (39%), floods (22%) and flooding/waterlogging (29%) occur in the southern region of Brazil, in the states of Rio Grande do Sul, Santa Catarina, and Paraná (Brazil 2013). Santa Catarina was one of the Brazilian states with the highest concentration of relative flash floods between 2008 and 2012, and Paraná was one of the most affected by inundations (Brazil 2013).

The southern region of Brazil comprises the states of Paraná, Santa Catarina, and Rio Grande do Sul, covering approximately 577,000 km² with a population exceeding 30 million inhabitants (IBGE, 2024). This region is characterized by a subtropical climate with well-distributed rainfall throughout the year. However, it exhibits significant inter-annual and seasonal variability influenced by large-scale atmospheric circulation patterns, particularly the El Niño-Southern Oscillation (ENSO) and the South Atlantic Convergence Zone (SACZ) (Grimm et al. 2000; Reboita et al. 2010).

Therefore, the adoption of empirical-based predictive and mitigating measures is crucial for reducing the diverse impacts caused by disasters, which are becoming increasingly unpredictable (Canlas 2023). In the event of natural disasters, decision-making supported by an information system is essential (Wang 2022).

The systematization of a national disaster database in Brazil is a recent endeavor, with data on disaster events only available from 1991 onwards. The lack of qualified personnel for registration, definition, classification, and estimation of damages, influences the quality of the recorded data, leading to inconsistencies, particularly in the face of the large number of parameters considered, especially in small and medium-sized cities.

A significant challenge is selecting a suitable criterion to represent the magnitude of hydrological disaster events for comparative purposes. Given the subjective nature and immeasurable value of human life, it is important to identify which variables in Brazil's disaster database best quantify the severity of hydrological disasters. Additionally, understanding the specific rainfall patterns that contribute to the magnitude of events such as floods, inundations, and flash floods, as well as their spatial and temporal occurrence, is essential.

This study tests the hypothesis that the magnitude of large-scale flood disasters in Southern Brazil is fundamentally driven by multi-day precipitation accumulation rather than isolated single-day extremes. We posit that while isolated events exceeding P95/P99 thresholds (i.e. the 95th and 99th percentiles of the historical precipitation series distribution) can trigger localized flash floods, the transition to catastrophic regional disasters is modulated by atmosphere-land surface feedbacks. Specifically, we hypothesize that the pre-saturation of soils due to persistent synoptic systems plays a crucial role in the occurrence of floodings. To test this hypothesis, we quantify the relative contribution of isolated and accumulated events. We do so through a hierarchical ranking of disaster magnitude. Our goal is to provide insights on the physical mechanisms that translate atmospheric forcing into significant socio-economic impacts in subtropical mid-latitudes.

Research knowledge supports decision making, management, and planning actions aimed at preventing and mitigating disasters, promoting sustainable and resilient cities. In this context, our study investigates the incidence, magnitude and rainfall characteristics of the main disaster events occurring in the South of Brazil, specifically in the states of Rio Grande do Sul, Santa Catarina, and Paraná.

Table 1 Hydrological Disasters Group in Brazil: COBRADE Classification System

Subgroup	Code	Definition
Floods	1.2.1.0.0	Submersion of areas beyond the normal limits of a watercourse in zones that are not usually submerged. The overflow occurs gradually, generally caused by prolonged rainfall in lowland areas.
Flash flood	1.2.2.0.0	High-velocity, high-energy surface runoff generated by intense and concentrated rainfall, typically in small, steeply sloped basins. Characterized by a rapid increase in streamflow and sudden overflow of the channel. Possesses significant destructive power.
Flooding / Waterlogging	1.2.3.0.0	Exceedance of urban drainage systems' carrying capacity, leading to water accumulation on streets, sidewalks, and other urban infrastructure, due to intense rainfall.

Brazil, 2012; COBRADE (Brazilian Disaster Classification and Coding) (Brazil, 2024b)

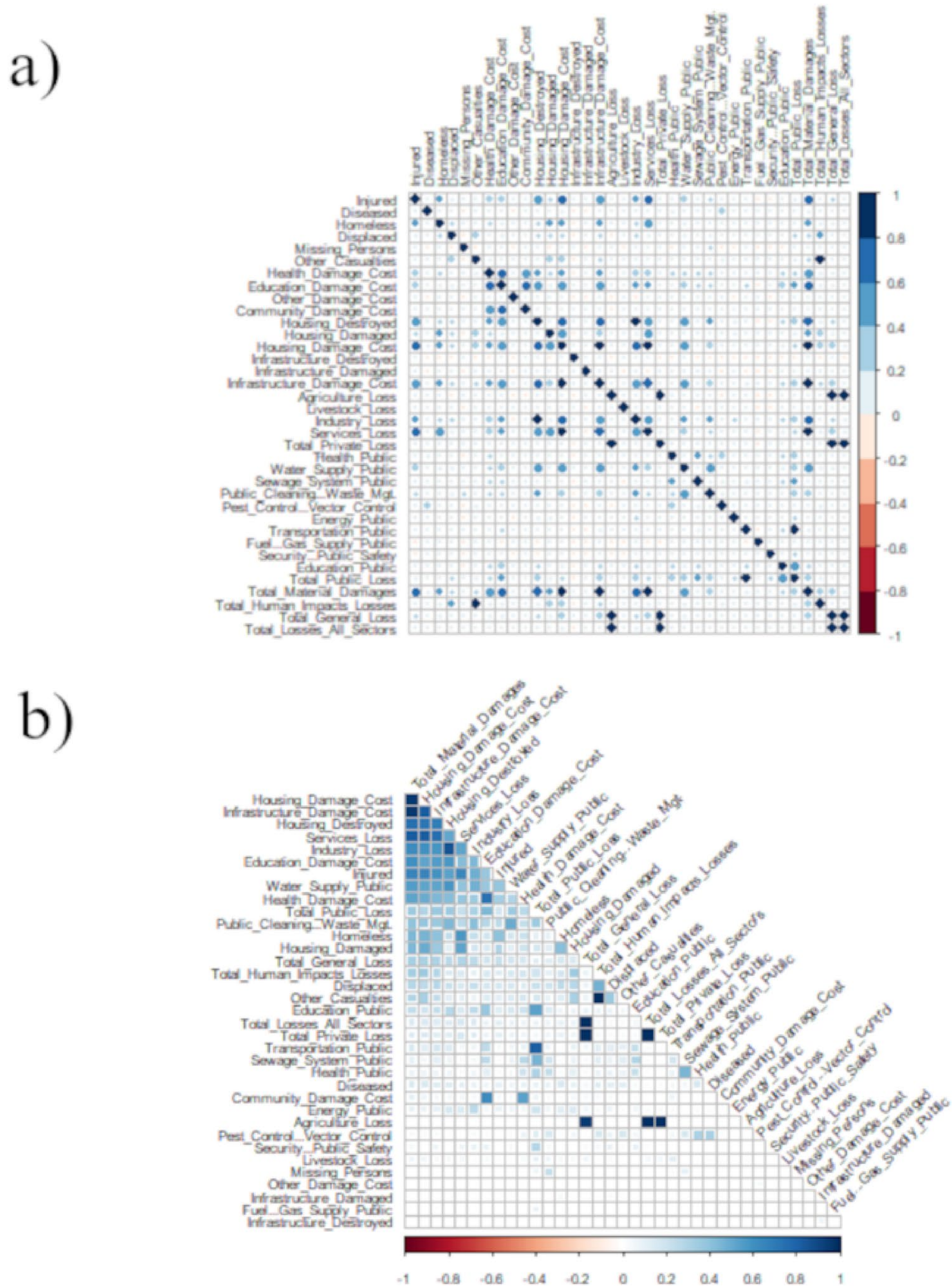

Fig. 2 (**a**) Graph of the correlation coefficients (colored boxes following the heatmap on the right) among the disaster variables; in order (from the top): Injured, Deceased, Homeless, Displaced, Missing, Other casualties, Health costs, Education costs, Other costs, Community costs, Housing destroyed, Housing damaged, Housing damage costs, Infrastructures destroyed, Infrastructures damaged, Agriculture losses, Livestock losses, Industry losses, Services losses, Total Private losses, Health public costs, Water Supply public costs, Sewage System public costs, Cleaning Waste public management, Pest and vectors control, Energy costs, Transportation public costs, Fuel and Gas supply public costs, Security and safety public costs, Education public costs, Total Public losses, Total Material Damages, Total Human Impact losses, Total General losses, Total Losses in all sectors. (**b**) FPC order indicating the variables that explain the maximal variance in the model; the FPC order goes from top to bottom, the most relevant variables are shown and explained in Table 2

2 Methods and Materials

The first phase of the research involved the selection of the hydrological disasters in southern Brazil. The second phase aimed to identify the variable within the disaster database that most accurately reflected the magnitude of these events. Subsequently, a third phase was dedicated to analyzing the characteristics of rainfall associated with the largest hydrological disaster events recorded in southern Brazil.

2.1 Study Area

The South Brazil region covers 576,774.31 km² and had a population of 29,937,706 in 2022, resulting in a population density of 51.9 people per square kilometer (IBGE, 2024, Fig. 1).

The climate in southern Brazil is predominantly subtropical (Cfa and Cfb), except for a small area in the extreme north where the climate is tropical (Am and Aw) (Alvares et al. 2014). Subtropical summers range from mild to hot, with temperatures between 25 and 30 °C, while winters are cool and can reach temperatures below 10 °C. Frost formation is

Table 2 Summary of the ten most relevant variables according to FPC hierarchy

Order	Damage	Unit	Type
1	MD_total (Health+Education+Housing+ Infrastructure+Community+Others)	Real (R$)	MD
2	MD_Damaged housing units	Real (R$)	MD
3	MD_Public infrastructure works	Real (R$)	MD
4	MD_Destroyed housing units	Real (R$)	MD
5	PRIEL_Services	Real (R$)	PRIEL
6	PRIEL_Industry	Real (R$)	PRIEL
7	MD_ Public education facilities	Real (R$)	MD
8	HD_Injured	People (Number)	HD
9	PUBEL_Drinking water supply	Real (R$)	PUBEL
10	MD_Public health facilities	Real (R$)	MD

MD=material damage; HD=human damage; PRIEL=private economic losses; and PUBEL=public economic losses. The evaluation considered total private material damage with the sum of losses private in agriculture, services, livestock, and industry. Total public material damage the sum of losses public related to health, water, sewage, cleaning, pests, energy, telecommunications, fuel transportation, security, and education. Total material damage includes the value of losses materials related to health, education, community, housing, infrastructure, and others. Total human damage the sum of people killed, injured, ill, homeless, displaced, missing, and others. Total losses the sum of public and private damages. Total general losses the sum of public, private, and total material damages

Table 3 Major hydrological disasters in Southern Brazil (1991–2024)

Order	Municipality	State	Date recorded	Type	Injured	Total_material_damage Reais (*R*$)
1	Blumenau	SC	23/11/2008	Flash flood	2383	1618922680,47
2	Itajaí	SC	23/11/2008	Flash flood	1806	1057143355,13
3	São João do Ivaí	PR	16/11/1997	Flash flood	0	355369909,89
4	Joinville	SC	22/11/2008	Flash flood	4	334900704,57
5	Blumenau	SC	11/09/2011	Floods	138	183032977,79
6	São Leopoldo	RS	20/06/2023	Flooding / Waterlogging	200	154921000,00
7	Ilhota	SC	24/11/2008	Flash flood	67	153868748,22
8	Londrina	PR	11/01/2016	Flash flood	0	151502080,63
9	Joinville	SC	10/03/2011	Flash flood	0	149081243,65
10	São Miguel do Iguaçu	PR	11/10/1996	Floods	0	144294077,44
11	Rolândia	PR	11/01/2016	Flash flood	1	135283794,85
12	Porto Alegre	RS	22/10/2015	Floods	0	134605356,29
13	União da Vitória	PR	11/06/2014	Floods	65	131798327,68
14	São José	SC	19/05/2010	Flash flood	9	109814074,58
15	Fazenda Rio Grande	PR	03/05/2004	Flooding / Waterlogging	6	101438731,72

SC: Santa Catarina, PR: Paraná, RS: Rio Grande do Sul

common. Rainfall is well distributed, with monthly amounts between 100 and 170 mm (Alvares et al. 2014), and annual totals ranging from 1050 to 2100 mm (Reboita et al. 2010).

Southern Brazil contributes over 17% to the country's GDP (Gross Domestic Product), it has the second major industrial park of the country and extensive areas dedicated to technologically advanced agriculture. The Southern region is also a major national exporter, with a focus on agricultural and agroindustrial products such as grains and poultry (IBGE, 2016).

2.2 Hydrological Disaster: Database, Magnitude and Geographic Distribution

The methodological procedures included the survey and analysis of spatial and temporal data on hydrologic disasters of the floods, flash flood and flooding/waterlogging (Table 1).

The hydrological disaster data were sourced from Integrated Disaster Information System - S2ID (https://s2id.mi.gov.br/) - a platform of the National System of Protection and Civil Defense of the Ministry of Integration and Regional Development of Brazil (Brazil et al. 2024a) of the time period 01/01/1991–28/05/2024.

In this study, disaster damage is defined as the multidimensional physical, social, and economic impact triggered by an adverse event, categorized into human, material, and environmental losses. Accordingly, magnitude is employed to quantify the severity of the disaster, serving as a metric for the total volume of damage expressed through financially estimated material losses, rather than its spatial scale or geographic extent.

The systematic collection of disaster data in Brazil is recent, with records extending from 1991. For each event, 53 variables were compiled and divided in three groups, detailing human, material, and environmental damages, along with private and public economic losses, as documented by local agents.

The recent systematization and standardization of a Brazilian national disaster database highlight the incompleteness of data (omissions), particularly in earlier records. Furthermore, analysis reveals methodological inconsistencies in data homogenization and damage estimation, as well as challenges in the classification of event typologies. These limitations are understandable given the vast territorial expanse and operational heterogeneity of the municipal entities, which are not always equipped with sufficient local human resources and infrastructure for the accurate recording of events.

The disaster data used were taken from the Brazilian Atlas of Natural Disasters from 1991 to 2012. The aforementioned data were expanded with the records from 1 January 2013 to 31 August 2024 to create a systematized, and standardized database.

The damage and loss values from 1994 to 2012 were adjusted for inflation using the General Price Index - Domestic Availability (IGP-DI), calculated by the Getúlio Vargas Foundation (FGV) (Brazil 2013). The IGP-DI is a comprehensive measure of inflation in Brazil that includes prices of raw materials, industrial goods, and final goods and services. This adjustment allowed for a more accurate comparison of values across different years.

All recorded variables of the hydrological disaster database were correlated using Pearson's correlation coefficient to identify the primary variable, which best represents the magnitude of damage, through a hierarchical ranking of the First Principal Component (FPC) (Fig. 2).

Among the recorded damage variables from hydrological disaster events in southern Brazil, we identified total material damages (MD), followed by material damages to housing units and public infrastructure works, as the most significant. Regarding human damages (HD), the number of injured individuals, private economic losses (PRIEL) in services and industry, and public economic losses (PUBEL) in potable water supply were the most relevant (Table 2).

For this study, the largest hydrological disaster events in Southern Brazil were identified based on an analysis of the total value of material damages at the municipal level (see Table 3). Specifically, events with estimated material damages exceeding 100 million Brazilian Reais were selected. This criterion was employed to pinpoint locations and regions requiring priority attention in flood disaster risk management due to the significant magnitude of their impacts. Applying this methodology resulted in the selection of 15 recorded hydrological disaster events, occurring across 13 different municipalities.

The frequency of hydrological disasters in the 13 municipalities that recorded events of greater damage magnitude was investigated, and these events were also spatially analyzed in Southern Brazil to identify areas requiring more attention. Based on historical records of flood disaster events from bibliographic sources and the disaster database.

The events with the highest recorded damages, with estimated losses exceeding 100 million reais, were mainly distributed in 6 locations (Fig. 1): (1) Serrana region (Vale do Itajaí) and eastern coast of Santa Catarina, including Blumenau, Joinville, Itajaí, Ilhota, and São José; (2) Greater Porto Alegre in Rio Grande do Sul, including Porto Alegre, and São Leopoldo, associated with the Guaíba River and the lagoon system of Lagoa dos Patos; (3) North-central Paraná, including Londrina, São João do Ivaí, and Rolândia (with Londrina being the second most populous city in Paraná and the fourth in the Southern region of Brazil); (4) Metropolitan region of Curitiba (Fazenda Rio Grande) and eastern coast of Paraná; (5) Eastern Paraná, centered on São Miguel do Iguaçu; (6) Southern Paraná, União da Vitória, on the border with Santa Catarina (Porto União), on the Iguaçu River.

The western region of Rio Grande do Sul, particularly Uruguaiana, which is associated with the floodplain of the Uruguay River, should also be considered when assessing the total damage resulting from hydrological disasters.

Across the analyzed municipalities, 139 flood events were documented, with a significant concentration (66%, 92 cases) in the Coastal Center region, followed by North (24%) and South (10%). The elevated occurrence of disasters in the Coastal Center can be attributed to its geomorphology, with mountainous terrain and confined valleys that favor the convergence of water flows, as well as to land occupation patterns, particularly in areas bordering watercourses with a history of flooding events.

Extreme hydrological disasters that significantly impacted numerous municipalities and were reported as

Table 4 Geographic distribution of hydrological disaster frequency by subgroup and state in Southern Brazil

State	Paraná		Santa Catarina		Rio Grande do Sul		Total by category	
Subgroup	Number	%	Number	%	Number	%	*Number*	*%*
Flooding	91	11	292	10	105	4	*488*	*8*
Flash Flood	609	72	2075	71	1656	69	*4340*	*70*
Flood	145	17	549	19	653	27	*1347*	*22*
Total (% regional)	*845*	*14*	*2916*	*47*	*2414*	*39*	*6175*	*100*

the largest in the history of the Southern Brazilian states occurred in 1983 in Paraná, 2008 in Santa Catarina, and 2024 in Rio Grande do Sul.

Paraná experienced one of its most severe hydrological events in July 1983. The disaster affected 41 municipalities, among them 32 declared a state of emergency and 6 a state of public calamity. Over 60,000 people were displaced and 18 lost their lives in the Iguaçu Valley (Paraná 2024). The municipality of União da Vitória was among the most severely affected areas, with 80% of the city inundated (França 1983).

In November 2008, intense and prolonged rainfall caused widespread flooding and landslides in the Itajaí Valley, Santa Catarina, affecting dozens of municipalities, more than 1.5 million people, and resulting in 135 deaths (Xavier et al. 2014). One of the largest magnitude disaster events recorded in the history of Santa Catarina, the rains of November 2008 and January 2009 left more than 80,000 people homeless and displaced, 60 municipalities in a state of emergency (SE), and 14 in a state of public calamity - ECP (World Bank, 2012).

Hydrological disaster occurred at the end of April and May in 2024, in the state of Rio Grande do Sul caused according to the National Confederation of Municipalities (CNM, 2024) 148 deaths, 816 missing persons, 91,400 homeless people, 651,000 displaced residents, 9,600 injuries and illnesses, and affected 3.1 million people. The event caused damage in 96.2% of the municipalities, namely 478 of the 497 municipalities part of the state (Rio Grande do Sul, 2024). In terms of material damage, 96,500 housing units were damaged, 9,100 were destroyed, resulting in a total loss of over 105,600 units, housing losses amounted to R$4.6 billion (CNM, 2024; Rio Grande do Sul, 2024).

The magnitude of damage caused by these disasters, and their locations define the areas (municipalities) where the main hydrological disasters occurred in Southern Brazil. This corroborates and validates the adopted criterion of material damage value.

Although the analysis is spatially limited to the administrative unit of the municipality, it is important to highlight that extreme events can affect areas beyond these boundaries, considering the spatial scope of the hydrographic basin.

Our analysis revealed a high frequency of hydrological disasters in southern Brazil, with 6,175 events recorded between 1991 and 2024, averaging more than 180 per year. Flash floods were the most prevalent type of disaster, accounting for 70% of all events, followed by floods (22%) and flooding (8%). Santa Catarina was the most affected state, with 47% of the total events, followed by Rio Grande do Sul (39%) and Paraná (14%) (Table 4).

In Southern Brazil, we identified that 60% of flooding (292/488) and 48% of flash flood (2075/4340) events were recorded in the state of Santa Catarina. While the highest frequency of floods (653/1347) occurred in Rio Grande do Sul (48%).

Flash floods and floods are responsible for the most significant hydrological disaster events. The municipality of Blumenau, Santa Catarina, was hit the hardest by a flood in November 2008, resulting in 1.6 billion reais in property damage and 2,383 injuries. Itajaí, also in Santa Catarina, suffered a similar fate on the same date. São João do Ivaí, Paraná, followed by Joinville and Blumenau, completing the list of the top five municipalities with the highest losses.

Municipalities with the most damaging events were not the ones hit more frequently. The locations of the largest magnitude hydrological disaster events (Blumenau, Itajaí, São João do Ivaí) do not necessarily correspond to those with the highest recorded frequencies (Rio do Sul, Joinville, and Itajaí) (Fig. A1). The frequency of hydrological disaster events showed no statistically significant linear relationship with the total value of recorded material damages ($R = 0.249$, $p < 0.184$); the municipalities that experienced the highest single-event damages did not correspond to those with the highest frequency of flood disasters. This observation underscores the complexity of disaster risk, indicating that while some areas may frequently experience hydrological events, the most devastating impacts can occur in distinct, less frequently affected locations, necessitating varied risk mitigation strategies (Kron 2008; Jackson 2016).

2.3 Rainfall Data: Source and Quality Control

For each of the 13 localities where hydrological disaster events occurred, we selected the rainfall station with the longest available rainfall data series from the existing database. The selection was made using the Hidroweb tool's maps and historical series (https://www.snirh.gov.br/hidroweb/), following a spatial and temporal assessment of available stations. Rainfall stations were chosen based on their proximity to the hydrological disaster locations (within either the affected municipality or an adjacent one). Key selection criteria also included: the availability of consistent historical rainfall data series with minimal gaps over extended periods; a recent monitoring period (e.g., extending to 2023); data availability coinciding with the investigated disaster registration dates; and location in landscape units representative of the disaster site's conditions, encompassing similar relief and exposure to water body influence (e.g., coastal proximity).

Daily rainfall series used in this study belong to stations managed by official institutions: Agricultural Research and Rural Extension Company of Santa Catarina (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina – EPAGRI), Water and Land Institute of Paraná (Instituto

Table 5 Annual trends of selected indices

Locality (Event)	Period (month/year)	cdd annual	prcptot annual	r20mm annual	sdii annual	r95p annual	r99p annual
Blumenau (1, 5)	01/1941 - 03/2024	0.00	5.18*	0.11*	0.03*	2.32*	0.00
Itajaí (2)	01/1941 - 12/2023	0.01	1.18	0.03	0.01	1.73*	0.00
São João do Ivaí (3)	04/1967 - 05/2023	0.22*	-2.60	-0.02	0.10**	0.79	0.00
Joinville (4, 9)	05/1977 - 07/2024	0.00	5.01	0.06	-0.06*	0.74	3.82*
São Leopoldo (6)	01/1964 - 09/2024	-0.11*	7.68*	0.10*	0.04*	5.92*	2.45*
Ilhota (7)	09/1927 - 03/2024	0.00	1.22	0.05	-0.00	0.59	0.00
Londrina (8)	01/1961 - 11/2024	0.15**	6.12*	0.16*	0.07*	2.78*	0.35*
São Miguel do Iguaçu (10)	08/1962 - 05/2023	0.05	-2.92**	-0.06	-0.01	-0.02	0.00
Rolândia (11)	12/1975 - 05/2023	0.28*	-6.34**	-0.16*	0.05*	1.32**	0.45*
Porto Alegre (12)	01/1961 - 12/2024	-0.06*	4.77*	0.09*	0.03*	4.28*	1.88*
União da Vitória (13)	02/1938 - 06/2024	0.01	2.24	0.07*	0.07*	2.77*	0.00
São José (14)	06/1948 - 12/2024	-0.04	6.47*	0.11*	0.02*	1.92**	0.00
Fazenda Rio Grande (5)	06/1964 - 06/2023	0.02	1.25	0.05	-0.00	0.58	0.00

Trends are indicated by statistical significance: *($p<0.05$), **($p<0.10$)

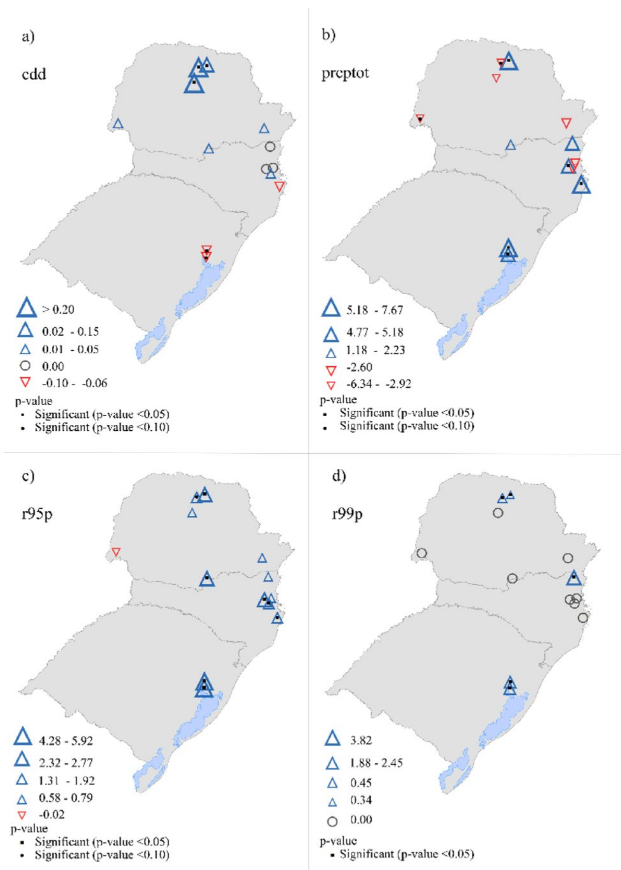

Fig. 3 Location and trend data of precipitation indices cdd (**a**), prcptot (**b**), r95p (**c**), and r99p (**d**) in the municipalities with the main flood disasters in southern Brazil; upward blue (downward red) triangles indicate increasing (decreasing) trends for each index, circles indicate absence of trend

Água e Terra do Paraná - IAT), National Meteorological Institute (Instituto Nacional de Meteorologia - INMET), National Water Agency (Agência Nacional de Águas - ANA) and National Center for Monitoring and Early Warning of Natural Disasters (Centro Nacional de Monitoramento e Alertas de Desastres Naturais - CEMADEN). All data are centralized and disseminated through the ANA, the custodian of Hidroweb.

A data quality control and gap reconstruction procedure was carried out for the selected representative rain gauge stations in each of the 13 localities (Table S1).

CoRain (Acquaotta et al. 2016; Guenzi et al. 2017) was used to rebuild daily gaps. To use CoRain it is necessary to have close measuring stations to compare data in the overlap period. This process involved statistical analysis, comparing rainfall data series, and applying a five-class weighting to the rainfall data (weak, mean, heavy, very heavy, and extreme). This resulted in a representative and consistent historical rainfall series for each locality.

The 322,892-day total rainfall data series underwent reconstitution for 11% (36,133 daily data points) of its records, employing CoRain. Consequently, only 1% (4,050 data points) of the final, utilized series contained unresolved data points (Table S1). This series was constituted with a minimum data interval of 47 years, from 05/1967 to 07/2024 (Joinville), and maximum of 97 years, from 09/1927 to 03/2024 (Ilhota).

Eight daily climate indices were selected to analyze precipitation variations and identify the types of rainfall events associated with the most significant floods in 13 municipalities. The indices included seven recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al. 2011; World Meteorological Organization [WMO], 2012): Consecutive Dry Days (cdd), Consecutive Wet Days (cwd), Number of very heavy rain days (R20mm), Total annual wet-day precipitation (prcptot), Daily rainfall intensity (SDII), Total annual precipitation from heavy rain days (r95p), and Total annual precipitation from very heavy rain days (r99p). The Standardized Precipitation Index (SPI) (McKee et al. 1993) was also used in the analysis. For these selected indices, the 1981–2010 period was used as the climate reference. Trends were subsequently determined across the entire historical series using the Mann-Kendall test (Mann 1945; Kendall 1975), with a significance level of 5%.

2.4 Flood-Generating Rainfall Characteristics

For the characterization of rainfall in the flood disaster event, the precipitation of the 30 days preceding the disaster registration date (included) was considered. This temporal window was adopted based on studies of floods in southern Brazil, which indicate extreme, intense, and accumulated precipitation in the preceding month as a key factor (Dias 2009; Xavier et al. 2014; Rucket et al. 2024; Marengo et al. 2024).

According to the World Meteorological Organization (WMO, 2018), heavy rain (or intense rain) is classified as that with a precipitation rate between 10 and 50 mm/h. Precipitation with rates exceeding 50 mm/h is considered very heavy or violent rain (WMO, 2018). It is important to highlight that, besides intensity, other factors such as the duration and spatial distribution of rainfall also influence the impacts of extreme events.

To characterize rainfall patterns associated with hydrological disaster events, we assessed precipitation characteristics during the 30-day period preceding each event. This assessment aimed to determine whether a disaster was primarily triggered by isolated extreme daily rainfall (i.e., daily rainfall exceeding a defined threshold) or by the accumulation of rainfall over several preceding days.

For each hydrological disaster event, we calculated the following metrics for the 30-day antecedent period: (1) number of extreme rainfall days: days with daily rainfall exceeding the 95p, threshold, the percentiles were calculated over the thirty-year reference period, 1981–2010. (2) Total rainfall: accumulated rainfall (mm) during the 30-day period. (3) Maximum daily rainfall: the highest rainfall total (mm) recorded within a 24-hour period during the 30 days. (4) Number of wet days: days with rainfall exceeding 1 mm during the 30-day period. (5) Daily rainfall density: the ratio of total rainfall to the number of rainfall days in the 30-day antecedent period. (6) Percentage of annual rainfall: the proportion (%) of the annual rainfall that occurred within the 30-day antecedent period. (7) Percentage of heavy rainfall exceeding 95p and 99p: the proportion (%) of the 30-day antecedent rainfall that exceeded the 95p and 99p thresholds.

Rainfall events that generated hydrological disasters in Southern Brazil were categorized as follows: (1) concentrated intense rainfall: Daily rainfall equaling or exceeding the intense rainfall limit (95p). (2) Accumulated rainfall from previous days: Daily rainfall totals whose cumulative sum over preceding days led to the disaster.

The software used included R (R Core Team 2016), the QGIS Geographic Information System (QGIS Development Team 2024), and Microsoft Excel.

3 Results

3.1 Precipitation Variations in Region Affected by Hydrological Disasters

Analysis of precipitation indices associated with duration, frequency, and amount (cdd, prcptot, r20mm, and sdii) in flood-affected municipalities of southern Brazil revealed different behaviors. Specifically, prcptot exhibited an increasing trend in 10 municipalities, but only in 5, Blumenau (5.18 mm/year), São Leopoldo (7.68 mm/year), Londrina (6.12 mm/year), Porto Alegre (4.77 mm/year), and São José (6.47 mm/year) the trends are statistically significant, contrasting with a decreasing trend observed in 3 municipalities, São Miguel do Iguaçu (-2.92 mm/year statistically significant), Rolândia (-6.34 mm/year statistically significant) and Sao Joao do Ivai (−2.599 not statistically significant) (Table 5; Fig. 3). The number of Consecutive Dry Days (cdd) indicates a decreasing trend in 3 municipalities but only in 2, São Leopoldo (-0.11 days/year) and Porto Alegre (-0.06 days/year, statistically significant and an increasing trend in 6 areas but only in 3, São João do Ivaí (0.22 days/year), Londrina (0.15 days/year, and Rolândia (0.28 days/year), the trends are statistically significant. Statistically significant decreasing trends were identified to Joinville (-0.06 mm/days for the Simple Daily Intensity Index (SDII, average daily wet-day rainfall intensity), and to Rolândia (-0.16 days/year statistically significant) for the number of days with rainfall≥20 mm (R20mm). Conversely, increasing trends prevailed for these indices in the other municipalities.

We identified an increasing trend in precipitation indices associated with intensity (r95p and r99p) in southern Brazil. A statistically significant increasing trend of r95p was observed in 9 out of 13 municipalities, and, for r99p, in 6 out of 13 (Table 5; Fig. 3).

These results are consistent with Global Circulation Model projections under climate change scenarios, which suggest an increase in the rainfall erosivity factor for southern Brazil (Riquetti et al. 2020; Panagos et al. 2022).

Table 6 Hydrological disaster events in municipalities with damage exceeding 100 million reais: Key characteristics and antecedent rainfall conditions

Order (Magnitude) Location (Municipality)	Disaster Registration Date	Total rainfall in the 30-day antecedent period (mm)	Annual rainfall (%)[1]	Maximum daily rainfall over the 30-day antecedent period (mm)	Days with rainfall > 1 mm in the 30-day antecedent period (number)	Amount of Heavy rain exceeding 95p (%)[2]	Extreme Rainfall (> r95p) (Number daily)	Class rainfall
(1) Blumenau	23/11/2008	760.5	39	263.2	24	61	5	Intense
(2) Itajaí	23/11/2008	386.9	22	71.3	27	46	3	Accumulated
(3) São João do Ivaí	16/11/1997	207.9	14	38.9	11	0	0	Accumulated
(4) Joinville	22/11/2008	497.6	21	120.0	27	36	2	Accumulated
(5) Blumenau	11/09/2011	488.9	25	121.1	14	78	6	intense
(6) São Leopoldo	20/06/2023	301.2	19	160.1	13	83	2	Intense
(7) Ilhota	24/11/2008	1047.1	62	275.3	24	75	7	Intense
(8) Londrina	11/01/2016	371.7	23	81.0	22	22	1	Accumulated
(9) Joinville	10/03/2011	395.4	17	67.5	26	17	1	Accumulated
(10) São Miguel do Iguaçu	11/10/1996	213.8	13	55.5	12	0	0	Accumulated
(11) Rolândia	11/01/2016	257.2	17	52.0	14	20	1	Accumulated
(12) Porto Alegre	22/10/2015	349.7	24	83.1	18	53	3	Intense
(13) União da Vitória	11/06/2014	452.1	26	264.9	6	77	2	Intense
(14) São José	19/05/2010	516.4	35	249.2	16	75	3	Intense
(15) Fazenda Rio Grande	03/05/2004	199.5	13	61.6	16	31	1	Accumulated
Average		**429.7**	**24.7**	**131.0**	**18.0**	**44.9**	**2.5**	

[1]Percentage of rain annual historical average, based on the years 1981 to 2010 (Blumenau = 1926.7 mm; Itajaí = 1726.0 mm; São João do Ivaí = 1436.9 mm; Joinville = 2381.4 mm; São Leopoldo = 1546.9 mm; Ilhota = 1702.0 mm; Londrina = 1593.6 mm; São Miguel do Iguaçu = 1645.3 mm; Rolândia = 1542.8 mm; Porto Alegre = 1462.6 mm; União da Vitória = 1717.1 mm; São José = 14.56.7 mm; Fazenda Rio Grande = 1508.6 mm). 2 In the 30-days antecedent hydrological disaster

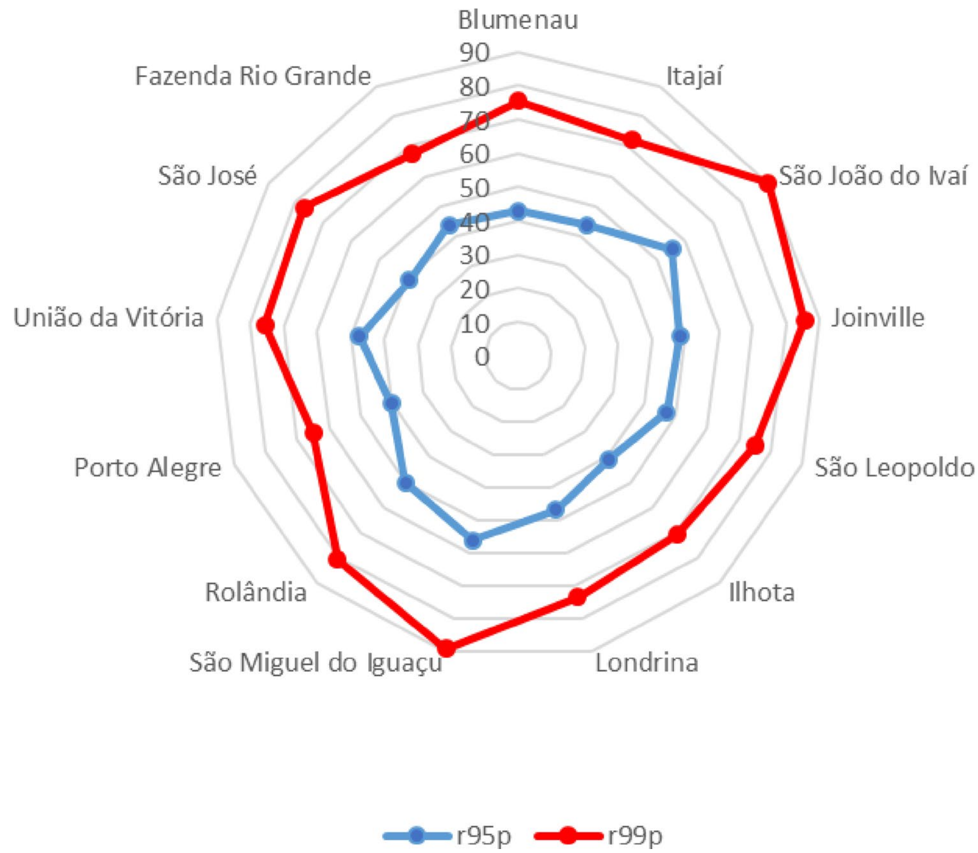

Fig. 4 Values of Extreme Rainfall Percentiles r95p (Blue) and r99p (Red) in Southern Brazil Locations with Flood Records determined for the 1981–2010 reference period

3.2 Rainfall Features in Significant Hydrological Disasters Events

The average 30-day antecedent rainfall for the 15 largest hydrological disaster events in Southern Brazil was 429.7 mm, with a minimum of 199.5 mm and a maximum of 1,047.1 mm. The average precipitation in the 30 days preceding the largest hydrological disasters in Southern Brazil was 25% of the annual rainfall. During these periods, there were, on average, 2.5 extreme rainfall events (exceeding the 95th percentile, 95p) per disaster, with rainfall amount 45% above the 95p threshold (Table 6). Furthermore, rain occurred on an average of 18 out of the 30 preceding days. These data demonstrate that extreme rainfall is a significant hazard factor for disasters in Southern Brazil within the context of climate change.

Accordingly, high-risk alerts regarding the occurrence of hydrological disasters in Southern Brazil should be issued when daily rainfall forecasts exceed 45% of the r95p value, or when accumulated rainfall on consecutive days surpasses 25% of the historically predicted annual rainfall.

The hydrological disaster events with the greatest damage magnitudes in southern Brazil were mainly recorded in spring and summer. The most intense rains in the region resulted from unstable meteorological systems, primarily associated with the movement of the Polar Atlantic Front (cold) and convective storms (Mendonça and Danni-Oliveira 2007). Rainfall in disaster events exceeded monthly historical averages, causing river levels to rise and, consequently, flooding. Intense rainfall leads to sudden and flash floods. In general, flash floods are concentrated in the summer and spring months (Brazil 2013), associated with the formation of local convective rainfall, Mesoscale Convective Complexes, and the entrance of cold fronts (Andrade et al. 2023).

A strong positive linear relationship (Pearson's $R = 0.787$, $p < 0.001$) was observed among the 15 largest hydrological disaster events when comparing maximum 24-hour intense rainfall to the total accumulated rainfall during the 30-day antecedent period. Hydrological disasters in the Serra and Litoral Catarinense Coastal regions (Blumenau, Ilhota, and Itajaí), alongside those in Londrina and Porto Alegre, were characterized by a total 30-day antecedent rainfall that significantly exceeded the long-term trend line. This feature differentiates these events from others that were primarily attributed to maximum 24-hour rainfall (Fig. 4).

In the municipalities where the main disasters associated with flooding are recorded, the average number of days with rainfall exceeding the 99th percentile (r99p) during the antecedent 30-day period was less than one. For the 95th percentile (r95p), the average was 1.7 days (Fig. 4). The value of r95p ranged from 39.2 to 56.2 mm, and that of r99p ranged from 64.8 to 90.0 mm.

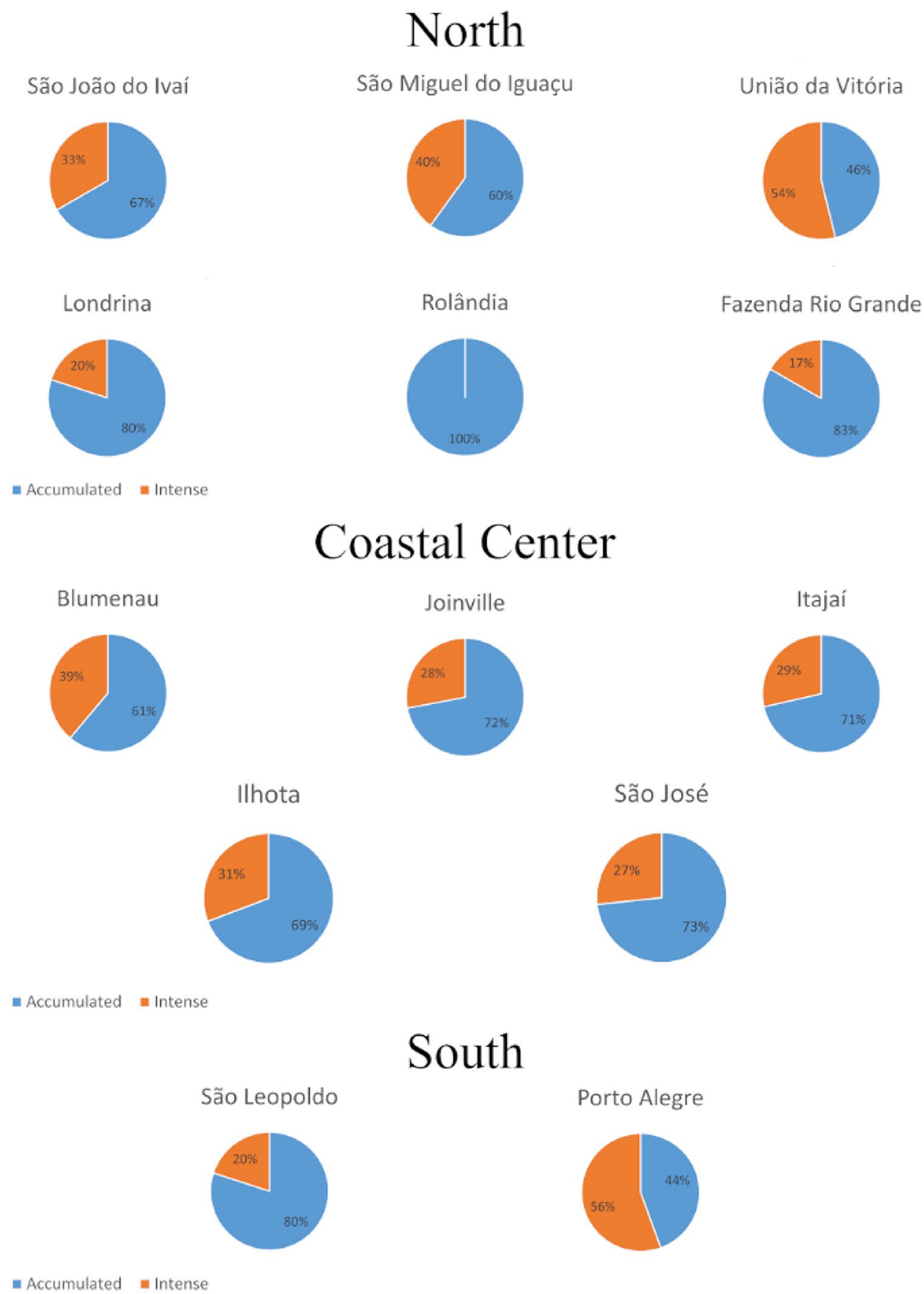

Fig. 5 Pie charts representing the percentage of accumulated (blue) and intense (orange) extreme precipitation events which affected the municipalities of the southern region of Brazil; North, Coastal Center, and South reflect the geographical collocation of the municipalities within the studied area. Intense rainfall is event where precipitation exceeds 50% of the heavy rain threshold (r95p), which is the 95th percentile

70% of the main hydrology disasters in southern Brazil can be attributed to accumulated rainfall, while the remaining 30% to intense rainfall (Table 6) which exceed 50% of the heavy rain threshold (r95p) − 95th percentile (Table C1).

Concentrated intense rainfall was strongly linked to major hydrological disasters in Porto Alegre (56%) and União da Vitória (54%) (Fig. 5). In contrast, accumulated extreme rainfall was more prevalent in the remaining municipalities. This highlights that hydrological disasters frequently arise from the synergistic impact of intense, high-volume, and sustained extreme rainfall.

3.3 Precipitation Spatiotemporal Variability and Trends: Implications for Hydrological Disasters in Southern Brazil

The investigation revealed the absence of a singular characteristic defining flood disasters in southern Brazil, whether in terms of a consistent spatial or temporal pattern of intense or accumulated precipitation. The intricate interplay of multiple conditioning factors demonstrates the complexity and diversity that shape hydrological disasters in the region.

Our findings reveal a complex spatial pattern in precipitation trends across key flood-prone regions of Southern Brazil. While some areas experienced a long-term increase in total annual rainfall, others, such as Rolândia and São Miguel do Iguaçu, showed a contrasting declining trend. However, despite this regional variability in overall precipitation, a uniform and statistically significant increase was observed in the number of extreme rainfall events, specifically those exceeding the 95th and 99th percentiles, suggesting that regional flood events are likely to intensify in both magnitude (the hazard). In the absence of actions and interventions to reduce vulnerability and population exposure, this intensification will directly amplify future socioeconomic damages and losses associated with these disasters.

3.4 Atmospheric mechanisms and multi-scale drivers of disaster magnitude

Our analysis reveals that 10 of the 15 largest flood disasters (67%) were associated with quasi-stationary frontal systems persisting for 3 to 7 days over Southern Brazil (Cavalcanti et al. 2021). These systems were characterized by slow propagation velocities (<5 m/s) and enhanced moisture convergence from the Atlantic and Amazon basins, a pattern frequently linked to atmospheric blocking and the intensification of moisture channels within the South Atlantic Convergence Zone (Reboita et al. 2010; Fernandes and Rodrigues 2018; Lavin-Gullon et al. 2021). Beyond synoptic forcing, the disaster magnitude (defined here as the volume of financially estimated material losses) was significantly amplified by multi-scale interactions (Lavin-Gullon et al. 2021).

This moisture convergence is further intensified by the South American Lower-Level Jet (SALLJ), which during the 2024 event, transported anomalously high moisture volumes from the tropical Atlantic and Amazon towards Southern Brazil, trapped by a persistent high-pressure blocking system (Clarke et al. 2024).

In all major events, volumetric soil moisture reduced infiltration capacity by 60–80%, converting persistent precipitation into massive surface runoff. This is consistent with the threshold-driven responses observed in humid subtropical catchments (Viglione et al. 2016; Uber et al. 2018). Although isolated convective systems triggered the remaining 33% of the events, these only reached high-magnitude status when the 15-day antecedent precipitation exceeded 150 mm. This confirms that disaster severity in Southern Brazil is not merely a function of instantaneous intensity, but rather a result of meteorological persistence and hydrological exhaustion (Marengo et al. 2021). Furthermore, the evident ENSO modulation reinforces how large-scale climate oscillations drive these high-magnitude financial impacts by shifting frontal tracks and intensifying moisture transport (Grimm et al. 2000; Cai et al. 2020; Petry et al. 2025).

The extreme precipitation thresholds identified in this study (P95: 22.5–38.7 mm; P99: 48.3–82.1 mm) demonstrate strict convergence with WMO (2023a and 2023b) standards, which established reference ranges of 20–40 mm/day for P95 and 40–80 mm/day for P99 in subtropical continental regions. This alignment confirms that regional climatic variability and orographic influences in Southern Brazil operate within the globally expected statistical range for extreme events. By anchoring our findings to these international benchmarks, we provide a robust baseline to validate IPCC AR6 projections, suggesting that atmospheric warming (governed by Clausius-Clapeyron scaling) will likely intensify these persistent systems (Zandonadi et al. 2016; Mantovani et al. 2024), thereby driving a projected increase in the frequency of high-magnitude disasters.

4 Discussion

Our findings provide compelling evidence that disaster magnitude in Southern Brazil is not merely a function of instantaneous intensity, but emerges from the critical convergence of meteorological persistence and hydrological exhaustion. This nonlinear response is driven by a synergy of reduced infiltration capacity, enhanced surface-atmosphere coupling, and an extended hydrological memory that sustains flood conditions well beyond the initial storm period. These threshold behaviors align with theoretical predictions from Earth System models (IPCC AR6, 2023) and empirical observations in other subtropical regions (Alvalá et al. 2024; Montanher et al. 2023). Furthermore, the 15-to-30-day accumulation window identified in this study represents the characteristic timescale for soil moisture depletion in this subtropical climate, suggesting that monitoring antecedent precipitation offers superior predictive skill compared to short-term (1–3 days) forecasts alone.

To contextualize these mechanisms, a comparison with other mid-latitude regions reveals distinct hydroclimatological patterns. While Southeast Australia shares a similar ENSO sensitivity, flood events there exhibit a stronger dependence on isolated peak rainfall, whereas in Southern Brazil, disaster magnitude is primarily dictated by antecedent accumulation (Cai et al. 2020; Martinez and Solman 2022). In Central Europe, although quasi-stationary frontal systems act as comparable drivers, the accumulation periods are typically shorter (5–10 days) due to the influence of strong orographic forcing and steep topography (Blöschl et al. 2019). The strongest analog to Southern Brazil is found in East Asia's Yangtze Basin; both regions share key synoptic features, such as the presence of persistent moisture channels (the SACZ and the Meiyu front, respectively) and 15-to-30-day accumulation windows. These similarities result in comparable disaster magnitudes, exacerbated by high population densities and significant economic concentration within flood-prone subtropical plains (Xia et al. 2021). This global comparison underscores that Southern Brazil's flood regime represents a specific subtropical archetype where meteorological persistence and soil saturation thresholds are the dominant determinants of socio-economic impact.

The observed upward trends in R95p and R99p indices across all municipalities provide a regional validation of IPCC AR6 projections, suggesting that climate warming (via Clausius-Clapeyron scaling) will primarily enhance meteorological persistence rather than merely peak intensity. Given that 67% of major disasters in the region are already driven by accumulated rainfall, this moisture-rich future indicates a 30–50% increase in catastrophic event frequency. This shift is expected to accelerate the attainment of critical soil moisture thresholds, transforming persistent weather systems into high-magnitude financial impacts with greater recurrence (Montanher et al. 2023).

Across the analyzed municipalities, 139 flood events were documented, with a significant concentration (66%, 92 cases) in the Coastal Center region, followed by North (24%) and South (10%). The elevated occurrence of disasters in the Coastal Center can be attributed to its geomorphological characteristics, characterized by a mountainous terrain with confined valleys that favor the convergence of water flows, and to land occupation patterns, notably in areas bordering watercourses with a history of flooding events. This is compounded by a mean annual precipitation gradient of approximately 692 mm between the Coastal North and South. Notably, increases in extreme rainfall have been observed alongside distinct seasonal shifts, with rising precipitation in summer, winter, and spring, and a general decrease in autumn (Murara et al. 2025). Furthermore, while the North and Central Inland regions show a trend of increasing consecutive dry days (CDD), the South and Extreme South exhibit a decreasing trend, although no clear increasing trend in consecutive wet days (CWD) is yet evident across the region.

Hydrological disasters in southern Brazil are primarily of hydrometeorological origin (BRAZIL, 2013). The damages often exceed the communities' capacity to cope, and are caused by intense and extreme rainfall, as well as the population's exposure and vulnerability to areas prone to floods and flash floods (Vestena 2017). The scale and magnitude of a disaster is determined by the population and infrastructure vulnerable to the hazard (flood, flash flood, and/or flooding). The damage caused by disasters generally reflects how people are vulnerable to dangerous events. The high economic losses have demonstrated the urgency of considering disaster risk, especially in cities, which tend to expand, often in an unplanned manner and without considering the occurrence of extreme hydrological events (Vestena 2017).

The lack of planning and the occupation of areas at risk of flooding increases the exposure to disasters, especially in cities, where more than 85% of the population lives in southern Brazil, the most populated area (IBGE, 2024). The occupation of unsuitable areas, especially floodplains, accentuates the occurrence of hydrological disasters with significant impacts on low-income populations.

Flooding disasters are the result of several factors: soil impermeabilization, which reduces rainwater infiltration and increases surface runoff; inadequate drainage systems with insufficient capacity to handle extreme rainfall; occupation of risk areas, making populations more vulnerable; and climate change, leading to more frequent and intense rainfall events (Tucci 2003). These factors necessitate a review of urban drainage projects and the adoption of more resilient measures (Tucci 2007).

The prevention and mitigation of hydrological disasters involve various areas of knowledge, primarily Hydrology (Vestena 2008), Climatology, and Meteorology, requiring an interdisciplinary analysis, as well as policies for land use management.

The homogeneity of historical series of disaster and meteorological data is essential for understanding disasters, considering the effects of climate change (Acquaotta and Fratianni 2014). Given that trend studies (Zandonadi et al. 2016) and predictive models indicate an increase in the frequency and magnitude of extreme events in southern Brazil (Trenberth 2011), maintaining high-quality, homogeneous historical datasets is paramount for developing adaptation strategies and climate-resilient infrastructure.

5 Conclusions

This study provides a new perspective on hydrological disasters in Southern Brazil, demonstrating that disaster magnitude is primarily a product of meteorological persistence rather than isolated intensity. The analysis reveals that the convergence of quasi-stationary frontal systems and pre-saturated soil conditions creates a nonlinear damage amplification effect. Our findings confirm that disaster magnitude in Southern Brazil is fundamentally driven by the interaction between antecedent land surface conditions, the duration of atmospheric forcing, and concentrated precipitation, which constitute the most critical determinants of socio-economic losses.

The estimated material damage is the variable that best depicts the magnitude of floods in southern Brazil.

The largest magnitude hydrological disasters in southern Brazil were associated with extreme and intense rainfall, exhibiting an average volume exceeding 429.7 mm per disaster event within the 30 days preceding the flooding. Events with the greatest magnitudes were determined by extreme rainfall.

The increasing trend of extreme rainfall, coupled with climate change, intensifies the frequency and magnitude of disasters in southern Brazil. This increase in intense extreme rainfall events may be associated with climate change and potentially exacerbates the risk of flood disasters in southern Brazil.

In summary, our analysis underscores a critical differentiation in the genesis of flood disasters in southern Brazil. While singular extreme precipitation events can undoubtedly inflict considerable damage, the overarching driver of large-scale hydrological catastrophes lies in the compounding effect of sequential rainfall events leading to substantial accumulated volumes. This pattern is strongly linked to persistent atmospheric systems, notably quasi-stationary frontal and cyclonic activity, with the South Atlantic Polar Mass playing a significant role in delivering intense and voluminous precipitation. These findings highlight the necessity of considering the temporal clustering and cumulative nature of rainfall, rather than solely focusing on isolated extremes, for improved risk assessment and mitigation strategies in the region.

Water dynamics operate at the spatial scale of the watershed; therefore, understanding rainfall patterns within the catchment area, as well as the occupation of flood-prone areas, is essential for analyzing hydrological disasters .

Thresholds for potential disaster alerts in Southern Brazil include daily rainfall forecasts exceeding 45% of the extreme event thresholds (r95p value), or accumulated rainfall on consecutive days surpassing 25% of the historically predicted annual rainfall. These empirically derived thresholds may inform operational parameters for early warning systems in the region.

Disasters result from the association of population and goods exposed to damage. The events present scalar magnitudes that exceed the administrative political division of the municipality. Future studies should assess the impact of climate change on the distribution and intensity of rainfall and its relationship with the frequency and magnitude of hydrological disasters in southern Brazil.

Constant monitoring and the creation of reliable and consistent hydrometeorological and disaster databases are crucial to understanding the causes and effects of disasters and supporting prevention and mitigation efforts. Real-time rainfall monitoring is important because, in addition to serving as a basis for zoning areas at risk of hydrological disasters, it can feed hydrological models for early warning systems.

Further research could focus on the application of the proposed methodology to other regions with similar climatological features. This could help to assess if accumulated extreme precipitations yield the same influence on flooding disasters globally. Moreover, our findings could be applied to precipitation regimes envisioned by future climate scenarios with the aim of strengthening adaptation efforts.

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Data Availability The hydrological disaster data are publicly available via the Integrated Disaster Information System (S2ID, https://s2id.mi.gov.br/), a platform of the National System of Protection and Civil Defense of the Ministry of Integration and Regional Development of Brazil (Brazil, 2024c). The processed rainfall time series, derived from gauge-corrected daily data using the corain methodology, are available upon reasonable request to the corresponding author.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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